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Lightning Protection

17.1	Ground Flash Density	17-1
17.2	Stroke Incidence to Power Lines.....	17-2
17.3	Stroke Current Parameters	17-3
17.4	Calculation of Lightning Overvoltages on Shielded Lines	17-3
17.5	Insulation Strength.....	17-4
17.6	Mitigation Methods	17-4
17.7	Conclusion	17-4

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The study of lightning predates electric power systems by many centuries. Observations of thunder were maintained in some areas for more than a millennium. Franklin and others established the electrical nature of lightning, and introduced the concepts of shielding and grounding to protect structures. Early power transmission lines used as many as six overhead shield wires, strung above the phase conductors and grounded at the towers for effective lightning protection. Later in the twentieth century, repeated strikes to tall towers, buildings, and power lines, contradicting the adage that “it never strikes twice,” allowed systematic study of stroke current parameters. Improvements in electronics, computers, telecommunications, rocketry, and satellite technologies have all extended our knowledge about lightning, while at the same time exposing us to ever-increasing risks of economic damage from its consequences.

17.1 Ground Flash Density

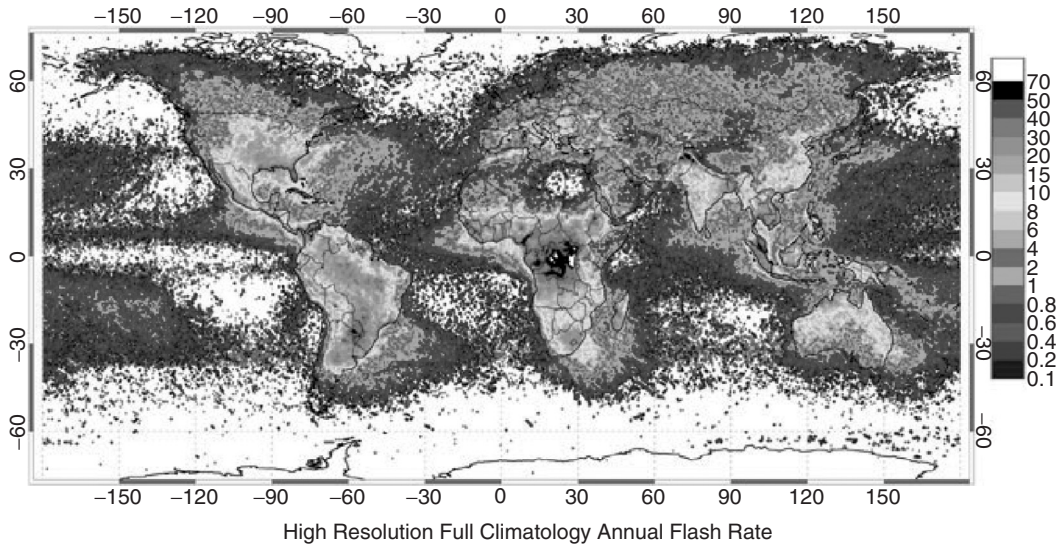
The first, negative, downward, cloud-to-ground lightning stroke is the dominant risk element to power system components. Positive first strokes, negative subsequent strokes, and continuing currents can also cause specific problems. A traditional indicator of cloud-to-ground lightning activity is given by thunder observations, collected to World Meteorological Organization standards and converted to ground flash density (GFD) [1,2]:

$$\text{GFD} = 0.04\text{TD}^{1.25} \quad (17.1)$$

$$\text{GFD} = 0.054\text{TH}^{1.1} \quad (17.2)$$

where TD is the number of days with thunder per year, TH is the number of hours with thunder per year, and GFD is the number of first cloud-to-ground strokes per square kilometer per year.

Long-term thunder data suggest that GFD has a relative standard deviation of 30%. Observations of optical transient density have been performed using satellites starting from 1995. These data have some of the same defects as thunder observations: cloud-flash and ground-flash activity is equally weighted and the observations are sporadic. However, statistical considerations now favor the use of optical transient density, for example, as reported by Christian et al. [5] over thunder observations.



High Resolution Full Climatology Annual Flash Rate

Global distribution of lightning April 1995–February 2003 from the combined observations of the NASA OTD (4/95–3/00) and LIS (1/98–2/03) instruments

FIGURE 17.1 Observed optical transient density per km² per year from Ref. [5]. The optical transient density can be used to estimate lightning ground flash density (per km²/year) by dividing the observed values by 3.0.

At present, a global estimate of GFD can be obtained by dividing the optical transient density in Fig. 17.1 by a factor of 3.0. This factor may vary across regions, possibly related to similar observed variations in the fraction of positive to negative flashes.

Electromagnetic signals from lightning are unique and have a high signal-to-noise ratio at large distances. Many single-station lightning flash counters have been developed and calibrated, each with good discrimination between cloud-flash and ground-flash activity using simple electronic circuits [3]. It has also been feasible for more than 30 years [4] to observe these signals with two or more stations, and to triangulate lightning stroke locations on a continent-wide basis. Lightning location networks [6] have improved continuously to the point where multiple ground strikes from a single flash can be resolved with high spatial and temporal accuracy and high probability of detection. A GFD value from these data should be based on approximately 400 counts in each cell to reduce relative standard deviation of the observation process below 5%. In areas with moderate flash density, a minimum cell size of 20 × 20 km is appropriate.

17.2 Stroke Incidence to Power Lines

The lightning leader, a thin column of electrically charged plasma, develops from cloud down to the ground in a series of step breakdowns [7]. Near the ground, electric fields are high enough to satisfy the conditions for continuous positive leader inception upward from tall objects or conductors. Analysis of a single overhead conductor with this approach [8] leads to

$$N_s = 3.8\text{GFD}h^{0.45} \quad (17.3)$$

where N_s is the number of strikes to the conductor per 100 km of line length per year and h is the average height of the conductor above ground in meters.

In areas of moderate- to high-GFD, one or more overhead shield wires are usually installed above the phase conductors. This shielding usually has a success rate of greater than 95%, but adds nearly 10% to the cost of line construction and also wastes energy from induced currents. The leader inception model [8] has also been used to analyze shielding failures.

17.3 Stroke Current Parameters

Once the downward leader contacts a power system component through an upward-connecting leader, the stored charge will be impressed through a high-channel impedance of 600 to 2000 Ω . With this high source impedance, compared to grounded towers or lines, an impulse current source model is suitable.

Berger made the most reliable direct measurements of negative downward cloud-to-ground lightning parameters on an instrumented tower from 1947 to 1977 [9]. Additional observations have been provided by many researchers and then summarized [10,11]. The overall stroke current distribution can be approximated [11] as lognormal with a mean of 31 kA and a log standard deviation of 0.48. The waveshape rises with a concave front, giving the maximum steepness near the crest of the wave, and then decays with a time to half-value of 50 μ s or more. The median value of maximum steepness [11] is 24 kA/ μ s, with a log standard deviation of 0.60. Steepness has a positive correlation to the peak amplitude [11] that allows simplified modeling using a single equivalent front time (peak current divided by peak rate of rise). The mean equivalent front is 1.4 μ s for the median 31 kA current, rising to 2.7 μ s as peak stroke current increases to the 5% level of 100 kA [11]. An equivalent front time of 2 μ s is recommended for simplified analysis [12].

17.4 Calculation of Lightning Overvoltages on Shielded Lines

The voltage rise V_R of the ground resistance R at each tower will be proportional to peak stroke current: $V_R = RI$. A relation between the tower base geometry and its resistance is

$$R = \frac{\rho}{2\pi g} \ln\left(\frac{11.8g^2}{A}\right) + \frac{\rho}{l} \quad (17.4)$$

where ρ is the soil resistivity (Ω m), g is the square root of the sum of the squares of the insulator extent in each direction (m), A is the surface area (sides + base) of the hole needed to excavate the electrode (m^2), and l is the total length (m) of wire in the wire-frame approximation to the electrode (infinite for solid electrodes).

For large surge currents, local ionization will reduce the second ρ/l contact resistance term but not the first geometric resistance term in Eq. (17.4).

The voltage rise V_L associated with conductor and tower series inductance L and the equivalent front time ($dt = 2 \mu$ s) is $V_L = LI/dt$. The V_L term will add to, and sometimes dominate, V_R . Lumped inductance can be approximated from the expression

$$L = Z\tau = 60 \ln\left(\frac{2h}{r}\right) \cdot \frac{l}{c} \quad (17.5)$$

L is the inductance (H), Z is the element antenna impedance (Ω), τ is the travel time (s), h is the wire height above conducting ground (m), r is the wire radius (m), l is the wire length (m), and c is the speed of light (3×10^8 m/s).

In numerical analyses, series and shunt impedance elements can be populated using the same procedure. Tall transmission towers have longer travel times and thus higher inductance, which further exacerbates the increase of stroke incidence with line height.

The high electromagnetic fields surrounding any stricken conductor will induce currents and couple voltages in nearby, unstricken conductors through their mutual surge impedances. In the case where lightning strikes a grounded overhead shield wire, this coupling increases common-mode voltage and reduces differential voltage across insulators. Additional shield wires and corona [11,12] can improve this desirable surge–impedance coupling to mitigate half of the total tower potential rise ($V_R + V_L$).

The strong electromagnetic fields from vertical lightning strokes can induce large overvoltages in nearby overhead lines without striking them directly. This is a particular concern only for MV and LV systems.

17.5 Insulation Strength

Power system insulation is designed to withstand all anticipated power system overvoltages. Unfortunately, even the weakest direct stroke from a shielding failure to a phase conductor will cause a lightning flashover. Once an arc appears across an insulator, the power system fault current keeps this arc alive until voltage is removed by protective relay action. Effective overhead shielding is essential on transmission lines in areas with moderate- to high-GFD.

When the overhead shield wire is struck, the potential difference on insulators is the sum of the resistive and inductive voltage rises on the tower, minus the coupled voltage on the phase conductors. The potential difference can lead to a “backflashover” from the tower to the phase conductor. Backflashover is more frequent when the stroke current is large ($5\% > 100$ kA), when insulation strength is low (<1 m or 600 kV basic impulse level), and/or when footing resistance is high (>30 Ω). Simplified models [11,12] are available to carry out the overvoltage calculations and coordinate the results with insulator strength, giving lightning outage rates, in units of interruptions per 100 km/year.

17.6 Mitigation Methods

Lightning mitigation methods need to be appropriate for the expected long-term GFD and power system reliability requirements. Table 17.1 summarizes typical practices at five different levels of lightning activity to achieve a reliability of one outage per 100 km of line per year on an HV line.

17.7 Conclusion

Direct lightning strokes to any overhead transmission line are likely to cause impulse flashover of supporting insulation, leading to a circuit interruption. The use of overhead shield wires, located above the phase conductors and grounded adequately at each tower, can reduce the risk of flashover by 95–99.5%, depending on system voltage.

TABLE 17.1 Lightning Mitigation Methods for Transmission Lines

Ground Flash Density Range	Typical Design Approaches
0.1–0.3 Ground flashes/km ² per year	Unshielded, one- or three-pole reclosing
0.3–1 Ground flashes/km ² per year	Single overhead shield wire
1–3 Ground flashes/km ² per year	Two overhead shield wires
3–10 Ground flashes/km ² per year	Two overhead shield wires with good grounding or line surge arresters
10–30 Ground flashes/km ² per year	Three or more overhead and underbuilt shield wires with good grounding, line surge arresters; underground transmission cables

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